ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

AUTONOMOUS UNDERWATER VEHICLE FOR SURFACE CLEANING OF A WAVE TANK

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Abstract. *This paper presents the conception, design, manufacturing and posterior control of an autonomous vehicle that moves around the bottom of the water tank at the Tanque de Provas Numérico of Escola Politécnica. The robot detects and dodges structures installed at the bottom of the tank. The robot has freedom of movement on three axes and its translation will be done by water pumps water jet. Microswitches will be responsible for sensing and distinguish obstacles from walls. Control system utilizes a programmable device with adequate acquisition rate in order to read switches signals. The robot is provided with a power circuit responsible for pump activation. The algorithm embedded allows the vehicle to sweep the majority of the bottom surface of the water tank.*

Keywords: *Autonomous vehicle; programmable control; underwater surface cleaning; control; automation*

1. INTRODUCTION

This work is entirely developed around the Tanque de Provas Numérico (for short, henceforth referenced as TPN) installed at Escola Politécnica de São Paulo and created through collaboration between the Brazilian petrol industry (PETROBRAS S.A.) and some of the major universities and research institutions in the country. TPN is a pioneer laboratory in hydrodynamics field, acting as a tool for project and analysis of “floating” structures destined for oil and gas extraction, simulating the whole production system behavior under a wide range of different environmental conditions, such as wind, waves and ocean currents. TPN is composed by several labs, among which the main purposes differ, but its core is a 120-processor cluster and a 14x14x4 meters wave tank, both seen in Fig. 1.

Figure 1. TPN cluster and wave tank.

As any other wave tank, TPN’s must be cleaned regularly. The process is normally accomplished by pumps installed on the walls of the tank, responsible for drawing the water and making it pass through a filter system, which restrains the largest dirt particles and then returns the water to the tank. Due to restrictions imposed by experiments conducted in the tank, many cleaning chemicals cannot be used in the water, so the process is done though a product that agglutinates dirt particles and cause them to be deposited on the bottom surface. A portion of this dirty with much of the sand that comes with the water used to fill the tank cannot be drawn from the bottom by the pumps and, thus, accumulates there. This accumulation of dirty can be a nuisance to the experiments conducted at TPN. Given the problem, the proposed solution presented in this paper is an autonomous underwater vehicle-robot capable of sweeping the majority of the bottom surface of the tank, agitating the particles and putting them on suspension, so that the pump-filter system can actually have full cleaning capability.

2. PROTOTYPE DEVELOPMENT

In order to create an efficient solution to the given issue, it is necessary to understand the robot’s working environment and which existing challenges must be overcome to achieve the proposed objective. This way, a group of essential features that assure the prototype’s functionality can be defined and later implemented.

2.1 Obstacles description

It is a project requirement to have the majority of the bottom surface of TPN's wave tank swept. The given surface is a plain square that has many different obstacles derived from structures of equipment used in the tank, which, if not taken in account, can hinder the vehicle's movement. For that reason, the robot must be able to sense and distinguish obstacles, taking actions according to the type of those encountered.

The relevant obstacles are described and positioned as it follows: scattered along the bottom surface are several 3 centimeters high threads of bolts (heads and shanks buried); in the center of the tank there is an area enclose by a 15 centimeters high, 4 meters radius circular rail; from the center of the circular area to somewhere on the rail is a 22 to 30 centimeters high, 4 meters long rotating metallic arm (it won't be rotating during the cleaning process); there are also two sinking holes with 23 centimeters of diameter, which placement is unimportant. Figure 2 is a photo of the tank.

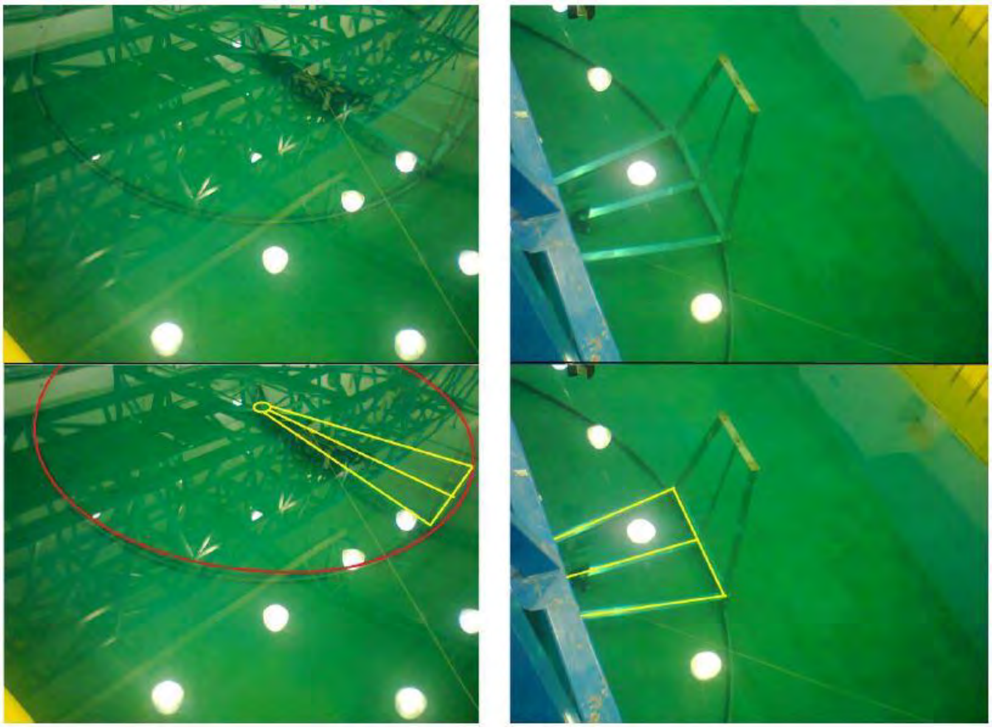

Figure 2. Obstacles on the bottom of the wave tank. In red the circular rail and in yellow the rotator arm.

The vehicle must enter the enclosed area in the center in order to sweep it, which means one of its features should allow the 15 centimeters high rail to be passed over. The metallic arm is the highest obstacle and doesn't need to be passed over, so it should be deviated from. The bolts can either be passed over or deviated from, but, since the last is more likely to be the easier and more reliable task, this should be the expected action. Also, the structure should be wide enough to prevent the vehicle from falling into the sinking holes.

Joining obstacles requisites, the initial proposal of sweeping the majority of the tank's bottom surface and the need to somehow agitate the dirt particles present there during the cleaning cycle, a solution that aims at efficiency and functionality is proposed.

2.2 Adopted solution

The final prototype is composed by two hexagonal aluminum plates as base and top of the structure, six folded rectangular plates make the vehicle's laterals and each of them has three mechanical sets to accommodate micro-switches that work as sensors. Robot's movement is done by six 1000 GPH (gallons per hour) bilge pumps, each installed on a different side of the vehicle, three with their outlets pointing down and three with outlets pointing sideways, with pumps of the same kind not being adjacent to each other. Horizontal movement is aided by six small radius wheels positioned under the base. The vehicle's underwater weight is also reduced by six PVC pipes sealed with air inside and fixed under the plate on top of the structure, aiding vertical movement. A photograph of the vehicle is presented on Fig. 3.

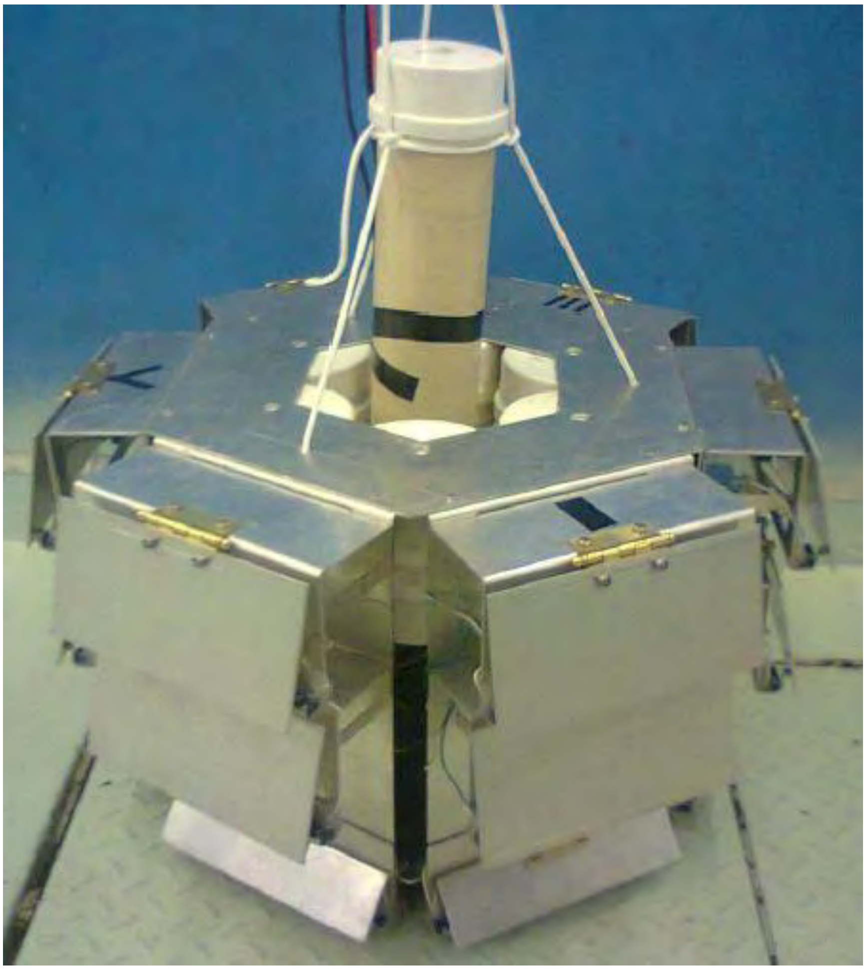

Figure 3. Complete prototype.

The robot is capable of horizontal movement, which means moving around the bottom of the tank, in six different ways by combined activation of one or two from the three flow pumps pointing towards its sides, which (together with better sensing capability and movement pattern) was the main reason to determinate a hexagonal shape to the vehicle and will be explained hereinafter. During most of the cleaning cycle the robot's wheels touch the ground but, in order to pass over the circular rail, the vehicle is also capable of vertical movement by simultaneous activation of all three pumps whose outlets point downwards, causing thrust which is enough to start upwards movement of the structure.

Sensing of obstacles is accomplished through the use of micro-switches, buttons that are activated whenever the robot's lateral touches an object. In order to distinguish between obstacles of different heights, installed on mechanical sets there are three levels of sensors on each lateral: the topmost sensors are able to touch only the walls of the tank and the central rotator arm; intermediate sensors may only come to contact with the circular rail; and lowest sensors are only activated by contact with bolts fixed on the bottom surface. All of this is valid assuming the vehicle is touching the ground and so derives its capability to differentiate obstacles, which will later trigger distinct actions on the robot.

2.3 Mechanical system

Considering that robot's movement is done by flow pumps, the direction to which each pump drives the structure cannot be reversed by simple inversion of electric voltage on its terminals. Thus, to move the vehicle around the spatial plane determined by the tank's bottom surface, three pumps attached to nonadjacent laterals and aligned with such lateral's horizontal midpoint are used in combination. Two horizontal pumps would not be enough to give the vehicle all necessary freedom of movement and four horizontal pumps would present two pairs of them over directly opposed directions, hindering such freedom as well, thereof derives the robot's hexagonal structure. The hexagon shape not only allows for saving in the number of pumps used and uniform distribution of them inside the structure (since there are three more pumps to execute vertical movement), but also, in comparison with a square or triangle shape, reduces the chances of hitting obstacles solely with the edges, situation in which the collision might not be detected, for the sensors are positioned on the faces and gaps lie on the edges. In comparison with a triangle shape, the incremented number of sides, and thus of sensors, allows for more accurate decision from the control algorithm and so for better pattern of movement to the vehicle.

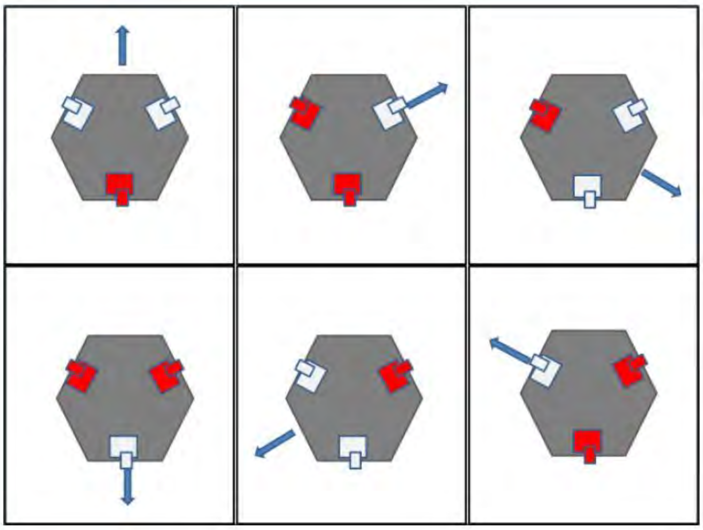

Figure 4. Combining activation of pumps to define robot's moving direction.

Figure 4 shows how six different directions of movement can be obtained with only three horizontal pumps. Pumps highlighted in red are the active ones at each moment and the blue arrow indicates how single or interpolated use of them can determine the direction to which the robot is being driven. This way, even with only the simple on/off control implemented on the pumps, the vehicle is able to roam the full extension of the tank's bottom surface.

Bilge pumps are projected to have optimal flow rate, which is not the most relevant characteristic to the present application, but rather each pump could be more efficient if their thrust force could be incremented. Thrust force is a function of flow rate and the area of the transversal section through which the fluid escapes the pump's body. In a situation of constant flow, the smaller the area of exit, the greater the thrust force is but, in a realistic situation, if the area becomes too tight, flow is drastically reduced. Thus, a model was developed to analyze through simulation if the work would be worth to relevantly increase pump force and, as a result, the conclusion was positive. This feature was projected, implemented and applied to all six pumps, a picture of one of the bilge pumps and its thrust optimizer is presented on Fig. 5.

Figure 5. Thrust optimizer and its coupling on a pump.

2.4 Electronic system

Adopted solution for obstacle detection was the use of micro-switches, buttons positioned under metallic panes on each of the vehicle's six laterals and on three distinct levels to distinguish between obstacles of different heights. Whenever the robot makes contact with environment obstacles or side walls of the tank, a specific group of the micro-switches is activated. To avoid water infiltration and button malfunction, sealing glue was placed over each of them and exposure tests were run to assure its underwater functionality and maintenance of electronic outputs. Figure 6 shows a lateral of the robot with all its components.

Figure 6. One of the vehicle's laterals with all its attachments.

Each micro-switch is in series with a pull-up resistor and those under the same pane are parallel to each other on the circuit, meaning they output the same electronic signal. Also, due to the fact that obstacles identified by upper sensors and lower sensors should always be deviated (which means they trigger the same action), there is no real need to distinguish between them, so their output signals are connected through an OR operation. Therefore, there are a total of twelve different input signals identifying sensor activation, two from each lateral, coming into the microcontroller, which is an Arduino Duemilanove. The scheme on Fig. 7 represents the outputs from one of the robot's laterals.

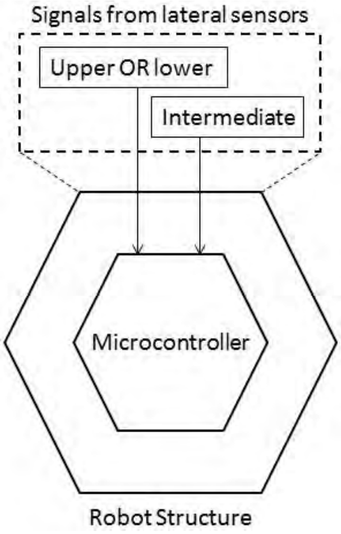

Figure 7. Entire logic of control is developed arround two bits of signal coming from each of the robot's laterals.

Through constant read of sensor input and analyses of internal variables, the algorithm embedded on the micro-controller is able to generate output signals to control pump activation and thus the robot's behavior. A power board composed by transistors and solid state relays able to distribute energy from an umbilical power cable is responsible for interfacing the output signals from the micro-controller with the on/off control of the pumps. There are a total of four one-bit signals coming out of the micro-controller and into the power board, one for each of the three horizontal pumps and one for the vertical pumps, which are always turned on/off as group since there is no roll or pitch control of the vehicle. Each pump is also provided with a 5 Ampere fuse.

As stated before, power comes to the circuit by an umbilical cable, which reaches out from the robot to the external surface and has buoys though its extension to avoid its sinking. The whole electronic circuit is encapsulated inside a PVC tube and all required wires come out of the encapsulation trough cable glands sealed with silicon glue, but the tube's lid can be opened with ease if necessary. A sequence of pictures of the full circuit and the encapsulation tube is presented on Fig. 8.

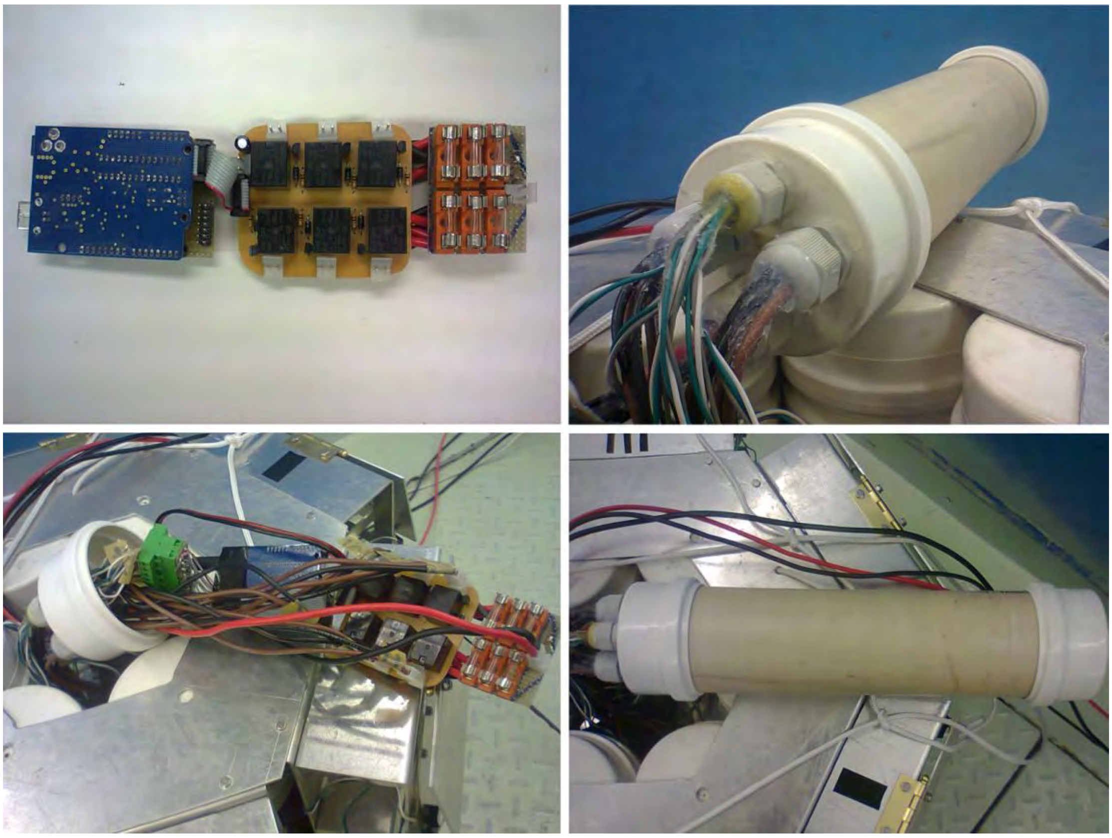

Figure 8. Complete electronic board and its encapsulation.

2.5 Control algorithm

Attempting to create a simple logic that guides the robot through its environment and avoids situations in which the vehicle could become stuck in obstacles or in repetitive patterns of movement, an embedded algorithm constantly reads input signals from the peripheral sensor buttons and takes action, by changing scheme of pump activation, whenever contact with any obstacles (or lack of contact for too long time) happens. The control algorithm does not keep track of the vehicle's position but rather guides its attitude whenever necessary.

Besides low-level functions responsible for reading sensor position, switching solid-state relays that control pump activation scheme and some other tasks, the present algorithm has three main segments, they are called the "Deflection logic", responsible for changing direction of movement whenever an obstacle that should be diverted is encountered; the "Jump logic", called when the circular rail should be passed over, executing a sequence of commands responsible for clearing the obstacle and continuing with the vehicle's previous path; and, finally, the "Watchdog logic", which constantly looks for predefined abnormalities in the vehicle's movement pattern and acts accordingly. Further along the paper, each of them will be explained in detail.

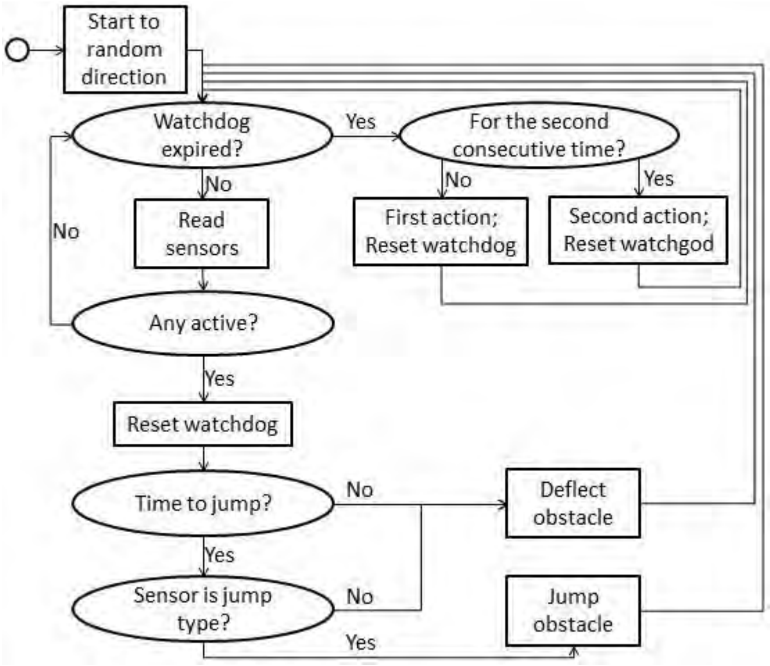

Figure 9. Simplified guidance logic.

A generic scheme of the main logic is displayed on Fig. 9. In summary, whenever the vehicle remains for longer than a preset period of time untouched by any obstacles, this is interpreted as if it's stuck somewhere, describing a circular pattern or even that some of its pumps has failed. In order to mitigate the effects of such occurrences, a watchdog with two instances (one for the first time the preset limit is reached and another for reaching it a second consecutive time) is ready to execute an emergency script. During regular operation, the vehicle executes two cleaning cycles, the first on the outer side of the circular rail for a predetermined period of time and the second on the inner side, after jumping onto it, which also lasts a previously fixed time. So on normal movement there is only a check for change of sensor state, in a positive case the algorithm must just decide if the encountered obstacle is jumpable or deflectable (if it's the circular rail or it's not, respectively) and whether it should be jumped over (if the robot has swept the first area for long enough) or deflected in that particular occurrence. Figure 10 shows an example of a possible simplified robot path.

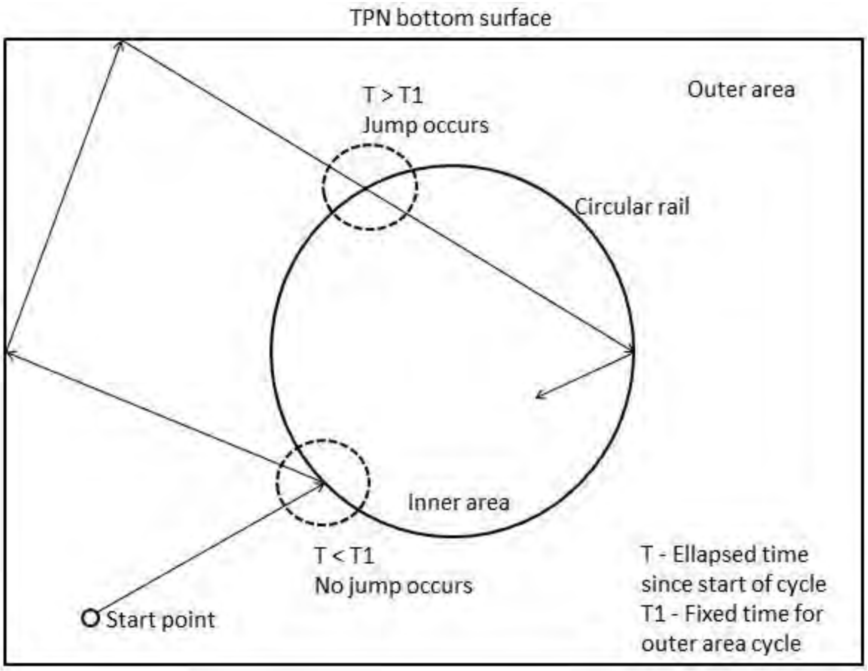

Figure 10. A very simple example of valid robot path.

Outer and inner cycles' times are calibrated empirically. After both are complete, the vehicle can automatically shut down and wait to be removed from the tank or can repeat the cycles indefinably until its power source is cut and then it is removed by the operator.

2.5.1 Deflection logic

The most frequent event during any of the cycles will be the contact with obstacles to be deviated. Bolts on the ground, all of the walls, the big rotator arm and even the circular rail will need to be deviated at some moment. In the occurrence of such kind of contact, vehicle's direction of movement should be changed in a manner that shifts the effort currently towards the obstacle away from it and, preferably, that leads the vehicle to a zone different than the one it has come from.

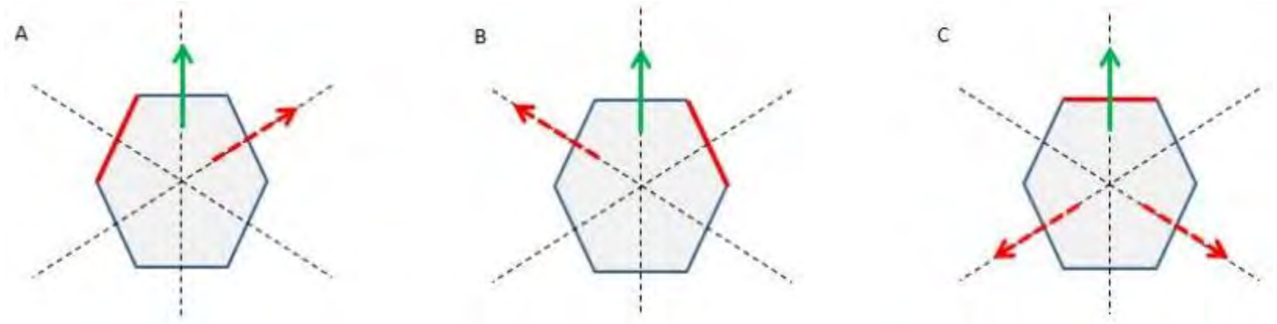

Figure 11. Logic of direction changing on the event of obstacle deflection.

As pump positioning always force the vehicle to move in the direction defined by one of the sides of its hexagonal structure, given a situation it is moving towards the direction of the green arrow, as Fig. 11 shows, whenever it hits a deflectable obstacle there is, theoretically, three distinct possibilities of sensor activation, shown as the red side of the hexagon: left, right or frontal (situations A, B and C, respectively). It must then be decided the new appropriate direction of movement to continue with robot's course. Considering what was stated before, in any of the situations, the direction indicated by the red arrow was found the most adequate to the propositions, meaning that the vehicle goes away from the obstacle and does not reverse direction, which would cause it to return the path it came from. Whenever an obstacle is hit on the sensor positioned to the left of the movement, as situation A, the course is changed to the right side of that direction. In an analog way, if the obstacle hits the sensor on the right side of the current direction of movement, situation B, course is changed to the left side. Give the situation of frontal encounter with an obstacle, on the own direction of movement, the right or left (but not directly) back directions are chose randomly (with a 50/50 percent chance) to be the new course, as the red arrows show in situation C. Activation of sensors positioned on the robot's three remaining sides is not contemplated in the described method because, in any situation the vehicle is moving to the correct direction, it's not possible to hit an obstacle with sensors that are not positioned on the half of the hexagon that defines its frontal area.

2.5.2 Jump logic

During the period of time between the end of outer cleaning cycle and start of the next cycle, before the vehicle was able to perform a jump onto the inner area of the circular rail, the control algorithm starts a process in which it "searches" for such obstacle. It means a simple thing: throughout the duration of this event, the intermediate of the three levels of sensors, which is able to connect exclusively with the circular rail, triggers a different action whenever activated. If the intermediate sensor positioned on any of the three edges of the hexagon's half frontal area (which includes the frontal edge and the two adjacent to it) is activated, a sequence of moves that attempts to pass the vehicle's structure over the obstacle is initiated. The direction in which the vehicle attempts to jump is always the same of the activated sensor, as seen in Fig. 12.

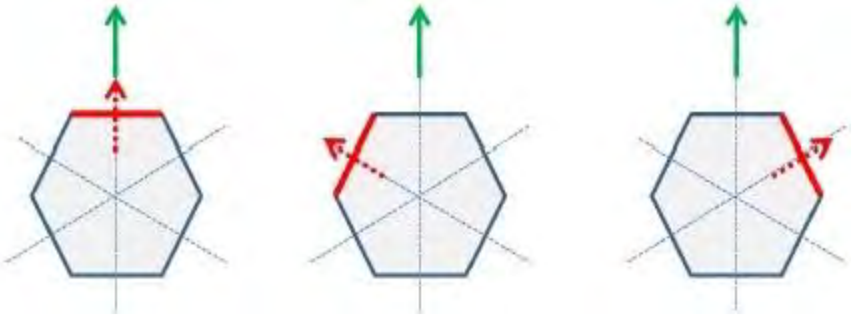

Figure 12. Logic of direction changing on the event of obstacle jump.

The figure shows the robot moving in the direction of the green arrow, the red edge represents the sensor activated at that time and the red arrow shows the direction to which the jump is performed. As before, only the three sides taken as “frontal” of the hexagon at the moment (for it depends on the current movement direction) are relevant for sensor activation, which means buttons pressed on any of the robot’s three other sides are ignored. Such jump attempt is a sequence of five movements, executed as follows:

Reverse - a small space between the vehicle and the obstacle is imposed by a backwards movement for a short period of time, to avoid any type of clutching during the jump; Rise - floatation pumps are activated to elevate the vehicle, so it stops touching the ground, and are then turned off after enough time to cause the vehicle to reach a certain height; Forward - horizontal movement pumps are turned on to move the robot in the direction of jump, causing it to pass over the obstacle, the vehicle also falls down slowly during this stage; Fall - all pumps are deactivated for enough time to assure the vehicle is once again touching the bottom surface; Continue - robot continues its horizontal movement in the same direction of the jump, following the deflection logic for all obstacles again. Figure 13 illustrates the described sequence.

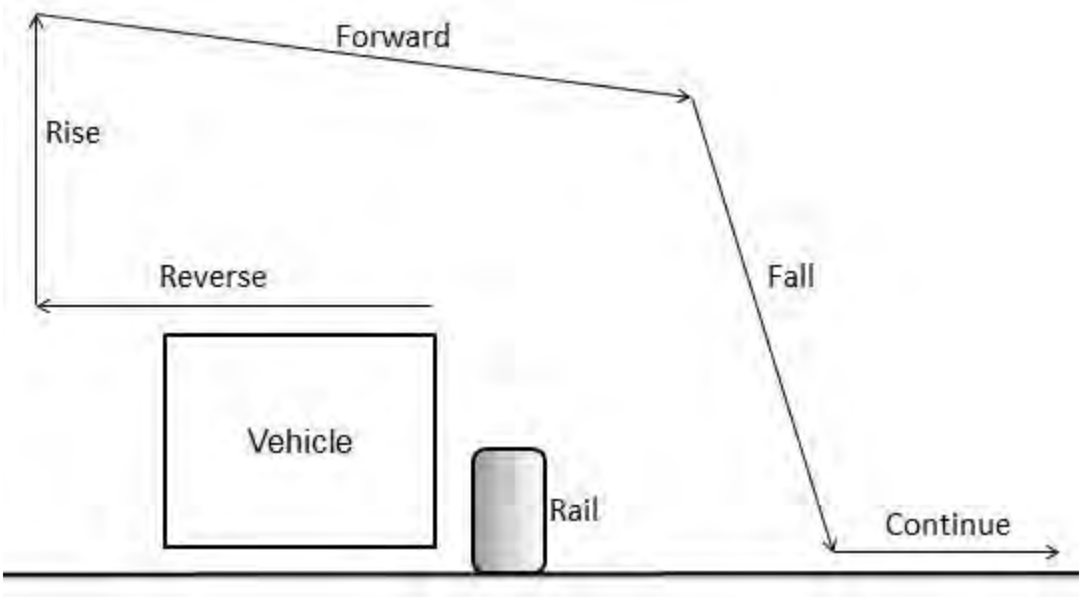

Figure 13. Five steps executed in order to pass over an obstacle.

Duration of each stage is calibrated empirically and, after completing the sequence, the control program assumes the robot is positioned on the inner area enclosed by the circular rail, continuing its cycle normally.

2.5.3 Watchdog logic

As the robot moves around the tank’s bottom surface, it may be subjected to unwanted situations that cannot be properly detected and specified by the sensors system, for example being stuck to some obstacle or misdirected by external forces, such as friction or drag. Since those situations cannot be completely avoided, a portion of the algorithm called “watchdog” was implemented to work as sentinel, in an attempt to mitigate the effect of such occurrences. It does not reinitiate the microcontroller as usual watchdog timers do, but was named so after the similarity with such systems, it rather starts the execution of a move sequence attempting to restore the vehicle to its regular operation.

The watchdog activates its first stage after a timer with preset value expires, and activates a second stage after that timer expires for two consecutive times; such timer is reset whenever there is a transition of sensor state, which means the robot is making or leaving contact with obstacles regularly (in other words, it is moving properly). The first action of the sentinel is simply to reverse the current direction of movement, a noninvasive and adequate help if the vehicle was to be lightly stuck to some obstacle or in a corner, or even performing unpredicted turns. The second stage starts a jumping process in the direction it should be moving, exactly as the jump performed to clear the rail, but this time with the objective of getting rid of anything that might be holding the robot more fiercely (maybe stuck under the structure) than the situations stage one of the watchdog could solve.

3. RESULTS

Tests of the robot demonstrated the prototype’s behavior to be close to the expected. The vehicle is able to sweep around the bottom surface of a tank, with the embedded program working particularly fine. Intended directions of movement are in fact obtained by combination of pumps activation, but not precisely, due to interference of external forces. Forces such as the umbilical cable drag and friction on roller wheels combined with complete absence of control over the robot’s rotation, cause it to turn erratically around its vertical the axis at radon moments, changing direction of movement or causing it to describe a circular path sometimes. The vehicle is very stable against unwanted rotations on the horizontal axes, never inverting vertical orientation during the tests, even on situations it had landed asymmetrically on top of obstacles.

It was also found the occurrence of small interferences on the sensors output signals, causing the microcontroller to identify nonexistent collisions of the robot. The exact origin of the noise was not identified but may be possibly related with magnetic fields originated on the switching of relays. The presence of such “ghost obstacles” was not considered harmful to the vehicle at all, for it happens with a low frequency and does not have a significant influence on the robot’s movement pattern, which is already quite erratic.

Another significant problem was found on the electronic system encapsulation. Even with the efforts of applying sealant tape and silicone glue to the interstices of the tube’s mobile parts, it was not enough to confer complete waterproofing to the system. Once the vehicle is submerged, a very small flow of water keeps leaking into the encapsulation, requiring the tube to be opened and drained every few hours or days, depending on the pressure differential imposed by the environment (water column). This situation restrains the continuous use of the prototype inside the TPN.

4. CONCLUSION

The implemented robot demonstrated itself to be functional and able to perform well on the given tasks, but it is more fragile than foreseen. The current prototype’s systems may be damaged if care is not taken during use and so, the vehicle would require a few improvements to be considered completely usable on its proper environment. If a second prototype was to be developed, likely suggestions would include the development of a more robust structure to accommodate the sensors, use of more powerful pumps to drive the vehicle, reduction of total chassis weight and enhancement of the waterproofing method over the electronic encapsulation.

5. ACKNOWLEDGEMENTS

The authors thank all those who, direct or indirectly, contributed to the fulfillment of the presented work.

6. RESPOSIBILITY NOTICE

Jefferson F. de Freitas, Luiz G. S. Simi and Eduardo A. Tannuri are the only responsible for the printed material included in this paper.